

# Development of Temperature Dependent Load-pull Analysis Techniques

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**Abstract** — Cryogenic on-wafer load-pull measurements are performed on GaAs MESFET ( $L_g=0.6\mu\text{m}$ ,  $W=300\mu\text{m}$  and  $L_g=1.0\mu\text{m}$ ,  $W=300\mu\text{m}$ ) power devices at 300K, 200K and 15K to demonstrate their performance improvement in output power and power-added efficiency when operated at reduced lattice temperatures. The power measurements were achieved at optimal bias condition to take into account the positive Temperature Coefficient (TC) that the On Breakdown Voltage exhibits. Additionally, an empirical temperature-dependent large-signal model valid to 18GHz is developed using experimental S-parameters and DC measurements to correlate actual load-pull measurements from 300K to 15K and to understand the performance improvements in output power and power-added efficiency. The model is also used to correlate the effect of the TC of Breakdown Voltage to power measurements.

## I. INTRODUCTION

With the rapid development of wireless communications, the power amplifier is a crucial component for both fixed and mobile applications. Optimizing its performance would have great impact on the system's overall performance. For mobile applications, the system battery and talk time are controlled by the power amplifier energy consumption, thereby demanding highly efficient power amplifier technology. For radar applications, the development of an efficient transmitter directly translates into improved radar range. A characteristic of great interest to both fixed and mobile applications is the behavior of the power amplifier as a function of temperature. The study of reduced-temperature operation of the power amplifier provides insights into the following questions: first, in an application such as ground-based radar; we can directly determine the benefit of reduced-temperature operation upon the power amplifier efficiency

and output power. Second, for applications where direct cooling is not practical, reduced-temperature operation allows us to study the effect of improved heat sinking and reduced device channel temperature. By reducing the channel temperature of the device, one expects an increase in electron mobility and carrier channel velocity resulting in an increase in transconductance, efficiency and gain.

In this paper, temperature dependent load-pull measurements are presented for GaAs MESFET power devices and an empirical temperature dependent large-signal model is generated. These models can be used to predict reduced channel temperature operation.

## II. EXPERIMENT

Cryogenic, on-wafer load pull measurements are achieved on GaAs MESFET power devices ( $L_g=0.6\mu\text{m}$ ,  $W=300\mu\text{m}$  and  $L_g=1.0\mu\text{m}$ ,  $W=300\mu\text{m}$ )[1]. The devices are mounted in a vacuum cryogenic chamber cooled by a closed cycle helium refrigerator, shown in Figure 1[2,3].

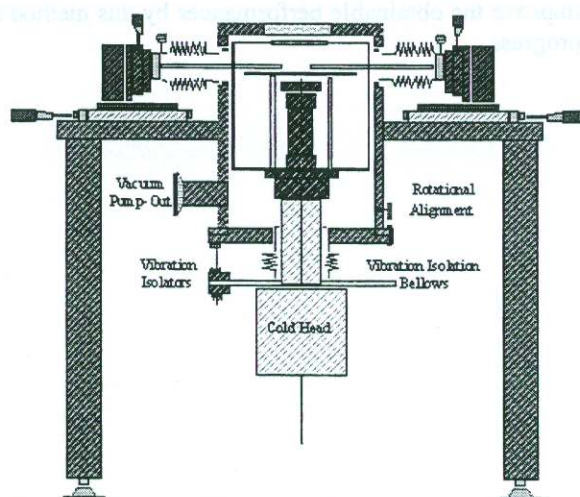


Figure 1: Schematic of the cryogenic microwave probe station.



Power measurements are performed at 300K, 200K and 15K. Constant output power and power-added efficiency (PAE) contour circles are generated at their 1dB compression point. These contours indicate the impedance termination necessary to achieve maximum power output and PAE. Decreasing the physical temperature of the device may cause a shift in the contours thus changing the impedance termination necessary for maximum achievable output power and PAE. Failure to consider this change will result in an inaccurate temperature comparison study. Additionally, S-parameters and current-voltage curves are measured at the different temperatures to implement the empirical large-signal model. Results are shown for the GaAs MESFET with  $L_g=0.6\mu\text{m}$ .

### III. TRANSISTOR MODELING

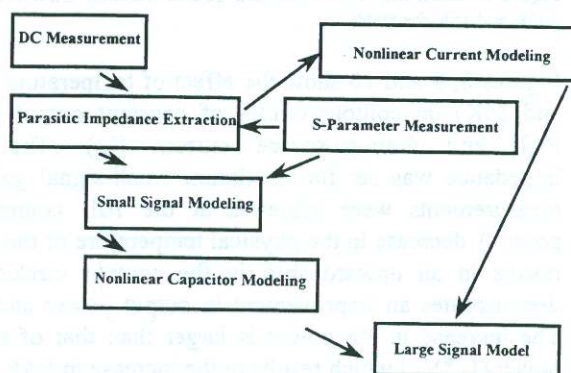


Figure 2: Large-signal modeling flow diagram.

The large-signal MESFET model is based on experimental S-parameters and DC measurements. The extrinsic parameters; parasitic resistance, inductance and pad capacitance are determined from cold FET S-parameters and the intrinsic capacitance from bias dependent S-parameters over a broad range of operating bias conditions[4]. In the model, the extrinsic parameters are considered bias independent and empirical nonlinear equations are used to formulate the nonlinear capacitors. To predict the harmonics of the fundamental signal, the current channel is modeled with a continuous function[5] and the diode current  $I_{gs}$  and breakdown current  $I_{dg}$  are obtained from DC measurements and are modeled with simple diode equations. By following these procedures, a large-signal model is implemented on the GaAs MESFET sample at both 300K and 15K in a harmonic balance simulator. The large-signal model is verified with actual experimental S-parameters and load-pull measurements. Figure 2 illustrates the procedures for the large-signal modeling and Figure 3 shows measured, simulated output power and PAE vs. input power level into 50-ohm termination at 300K and 15K.

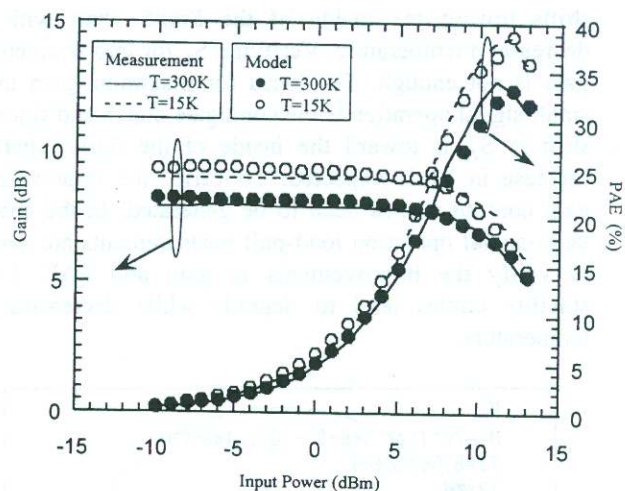


Figure 3: GaAs MESFET Measured, Simulated Pout and PAE vs. Input power level into 50-ohm termination at 300K and 15K (Freq= 6 GHz,  $V_{ds} = 3\text{V}$ ,  $V_{gs} = -0.8\text{V}$ ).

### IV. RESULTS

The GaAs MESFET's ( $L_g=0.6\mu\text{m}$ ) DC characteristics show an increase in the drain current (shown in Figure 4) and the device transconductance while operating at reduced temperature. The improvements are results of the increase in both the carrier channel velocity and electron mobility[6], which result in an increase in efficiency[7]. Additionally, Figure 4 illustrates the degradation of the On Breakdown Voltage ( $BV_{on}$ ).  $BV_{on}$  exhibits a positive TC[8,9].

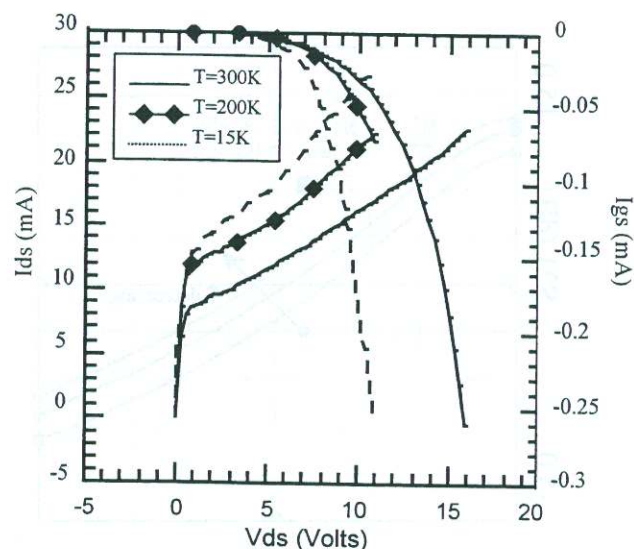


Figure 4: GaAs MESFET ( $L_g=0.6\mu\text{m}$ ,  $W=300\mu\text{m}$ ) DC Characteristics.

Figures 5, 6 and 7 show the S-parameters and the stability circles of the GaAs MESFET power device.  $S_{22}$  parameter



shifts toward the inside of the Smith chart with the decrease in temperature. Verifying  $S_{21}$  for improvements in gain is not enough. The locus for maximum gain under small-signal operation is the conjugate match and since the shift in  $S_{22}$  is toward the inside of the Smith chart an increase in  $S_{21}$  is expected. To verify the improvement, gain contour circles need to be generated. In the case of large-signal operation load-pull measurements are needed to verify the improvements in gain and PAE. Load-stability circles tend to degrade while decreasing the temperature.

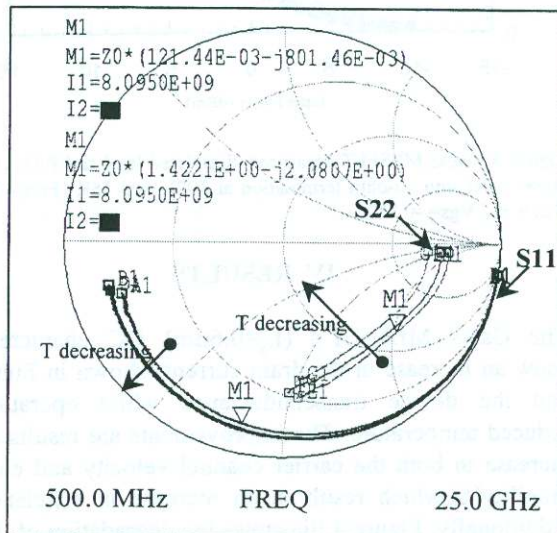


Figure 5: GaAs MESFET  $S_{11}$ ,  $S_{22}$  parameters at 300K, 200K and 15K.

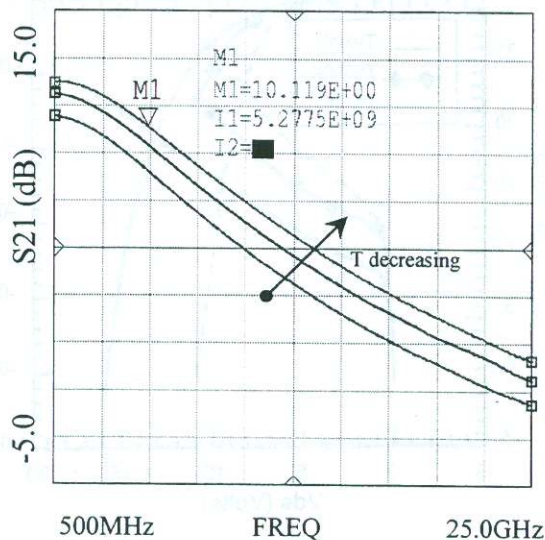


Figure 6: GaAs MESFET  $S_{21}$  parameter at 300K, 200K and 15K.

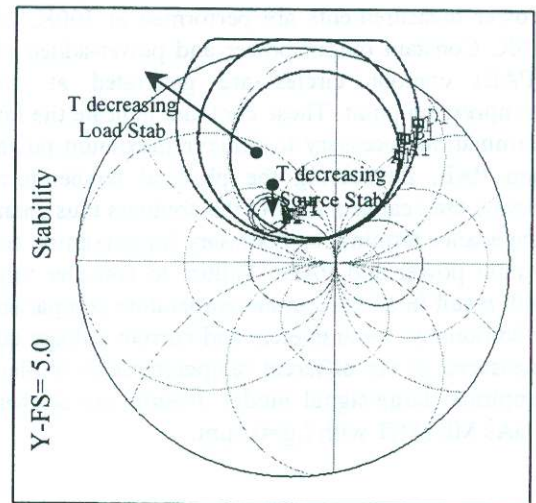


Figure 7: GaAs MESFET Load and Source Stability Circles at 300K, 200K and 15K for 8GHz.

Figures 8, 9 and 10 show the effect of temperature (300K and 15K) on contour circles of constant output power, PAE and drain-to-source current ( $I_{ds}$ ). The input impedance was set for maximum small-signal gain and measurements were achieved at the 1dB compression point. A decrease in the physical temperature of the device results in an upward shift in the contour circles. This demonstrates an improvement in output power and PAE. The increase in RF power is larger than that of the DC power ( $I_{ds} \cdot V_{ds}$ ) which results in the increase in PAE.

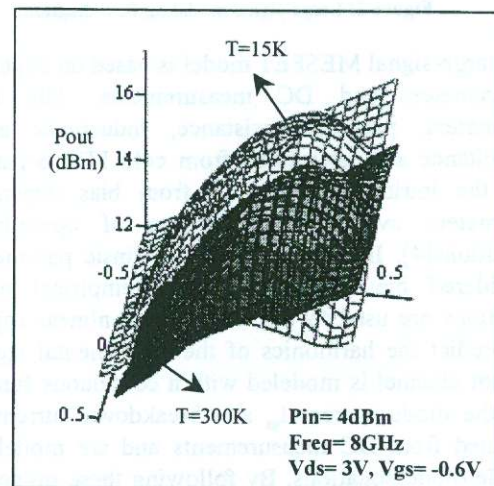


Figure 8: GaAs MESFET Pout vs. Load Gamma at 300K and 15K.



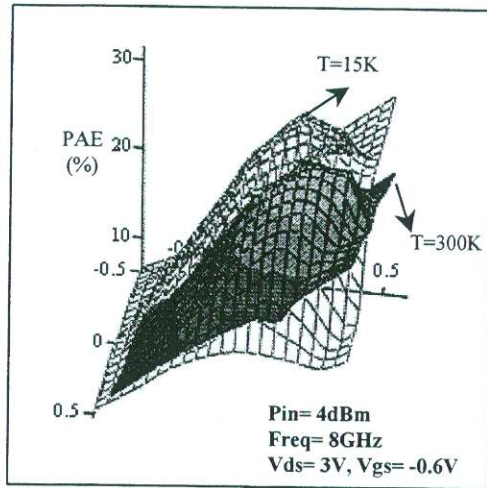


Figure 9: GaAs MESFET PAE vs. Load Gamma at 300K and 15K.

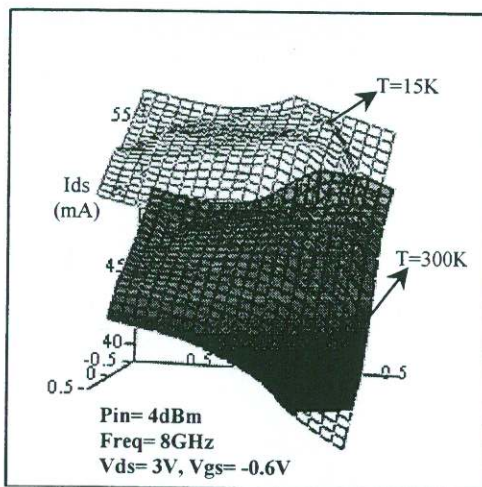


Figure 10: GaAs MESFET  $I_{ds}$  vs. Load Gamma at 300K and 15K.

Figures 11 and 12 show the gain and PAE as a function of input power and temperature for two different bias conditions. The input and output impedance was set for the conjugate match condition. Operating at the lower drain-to-source voltage results in an improvement in both gain and PAE. The higher bias condition results in higher 1dB compression points, however the gain at compression tends to degrade with reduced temperature of operation and the PAE is lower than at 300K. The breakdown voltage exhibits a positive temperature coefficient. This result applies to the other GaAs MESFET ( $L_g=1\mu\text{m}$ ,  $W=300\mu\text{m}$ ). Device technologies that are optimized for cooled operation will provide significantly enhanced performance.

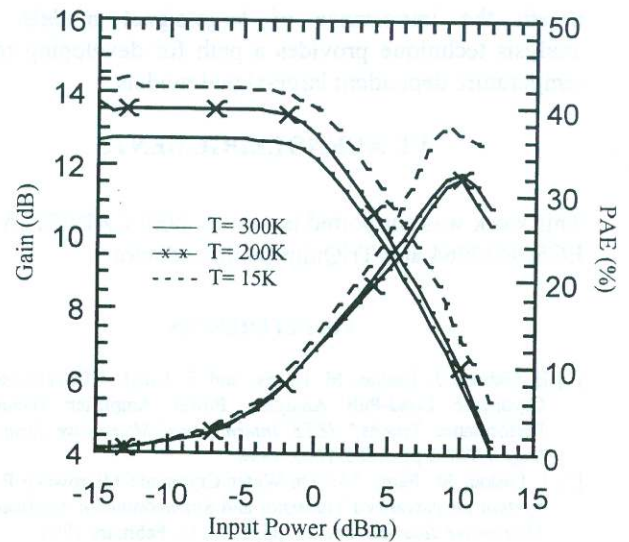


Figure 11: GaAs MESFET Gain and PAE vs. Input power at 300K, 200K and 15K. ( $V_{ds}=3\text{V}$ ,  $V_{gs}=-0.6$ ,  $\text{Freq}=8\text{GHz}$ ).

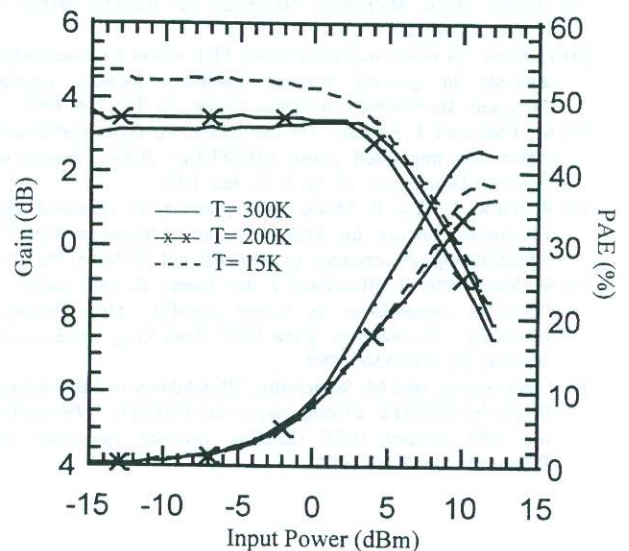


Figure 12: GaAs MESFET Gain and PAE vs. Input power at 300K, 200K and 15K. ( $V_{ds}=5\text{V}$ ,  $V_{gs}=-0.6$ ,  $\text{Freq}=8\text{GHz}$ ).

## V. CONCLUSION

We successfully performed on-wafer cryogenic load-pull measurements and developed an empirical large-signal model for a GaAs MESFET ( $L_g=0.6\mu\text{m}$ ,  $W=300\mu\text{m}$ ) power device at two different temperatures (300K and 15K). Detailed results and analysis show that the improvements in output power and PAE are due to the increase in the electron mobility and carrier channel velocity. Additionally, we showed that bias plays a major role for device technologies in which the On Breakdown Voltage exhibits a positive Temperature Coefficient,

herein the importance of large-signal models. This analysis technique provides a path for developing robust temperature dependent large-signal models.

## VI. ACKNOWLEDGEMENTS

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